RADIATION PROTECTION AT HIGH ENERGY HEAVY ION ACCELERATORS

H.-P. Weise
Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin
Unter den Eichen 87, D-10000 Berlin 45, Federal Republic of Germany

INTRODUCTION

The radiological impact in the environment of high energy accelerators is given by the following main contributions:

1. prompt radiation consisting mainly of neutrons which originate from shields;
2. activated air released from the accelerator building;
3. skyshine of neutrons emitted into the air above the accelerator.

Radiation exposure of the public due to activated ground water was found to be of no concern. Simple relationships have been derived which allow the calculation of the three dominant contributions to the radiation impact of heavy ion accelerators operating in the energy region between 0.4 and 2 GeV/nucleon.

CALCULATION OF THE NEUTRON DOSE RATE OUTSIDE SHIELDS

Assuming that the ion beam interaction zone can be regarded as a point neutron source (Fig. 1) the dose rate at the outer surface of the shield can be expressed in terms of the differential neutron yield per ion of the source, the effective fluence to dose conversion factor and the effective dose transmission factor of the shield. For thick shields ($>$ 500 g/cm²) the contribution of source neutrons below 100 MeV to the dose rate at the outer surface of the shield is only a few percent. Therefore to a good approximation the lower limit of the source neutron energy to be taken into account is chosen to be E_0 = 100 MeV. The effective quantities were calculated by folding the appropriate data for monoenergetic neutrons with measured and calculated spectra of neutrons produced in high energy heavy ion reactions [1]. Since the effective dose transmission factor for $\rho \cdot d > 500$ g/cm² can be described in terms of an exponential function and a dose buildup factor we obtain:

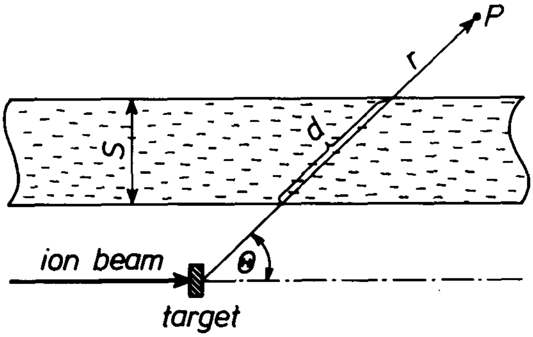

Fig. 1 Shielding geometry

$$\dot{H} = K \cdot \frac{1}{r^2} \cdot J \cdot \exp [- (\rho \cdot d) / \Lambda] \qquad (1)$$

The parameters K and Λ depend on the specific ion energy and on the neutron emission angle. Equ. (1) allows the straightforward estimation of the shield thickness $\rho \cdot d$ from the given dose rate limit. The necessary data are quoted in reference [1]. For comparison this method was applied to the lateral shielding of proton accelerators where other published data are available.

TABLE 1 Lateral shielding of multi-GeV proton and heavy ion accelerators by ordinary concrete or soil. E_i specific ion energy in GeV per nucleon; $[\rho \cdot d] = g \cdot cm^{-2}$

Reaction	$\dot{H}(\Theta = 90°) \cdot r^2/J$ ($\mu Sv \cdot h^{-1} \cdot cm^2 \cdot s$)	Comments
p thick iron target	$0.16 \cdot E_i \cdot \exp[-(\rho \cdot d)/108]$	this work
	$0.39 \cdot E_i \cdot \exp[-(\rho \cdot d)/103]$	O'Brien-method
	$0.16 \cdot E_i \cdot \exp[-(\rho \cdot d)/117]$	Moyer-method
Ne thick iron target	$5.7 \cdot E_i \cdot \exp[-(\rho \cdot d)/106]$	this work
	$2.6 \cdot E_i \cdot \exp[-(\rho \cdot d)/114]$	this work

The various shielding formulas for protons are in satisfactory agreement. For thick concrete shields ($\rho \cdot d \approx 1000$ g/cm²) the calculated dose rates differ by no more than a factor of two. For heavy ion beams the lateral neutron dose attenuation length is nearly identical to the proton value but heavy ion reactions yield much more neutrons than proton interactions at the same specific ion energy. This is simply a consequence of the larger number of interacting nucleons in heavy ion collisions. With respect to radiation protection this means that for the same specific ion energy and the same beam intensity a multi-GeV heavy ion accelerator requires considerably more shielding than a proton machine.

ACTIVATION OF AIR

With respect to radiological impact only a few gaseous radionuclides are of concern. The most important reactions and their effective cross sections are summarized in Table 2.

TABLE 2

Effective cross sections σ_{eff} (> 15 MeV) in mbarn of nuclear reactions induced in air by secondary particles produced by interactions of 2 GeV/u heavy ions.

		Targetnuclide		
Radionuclide	$T_{1/2}$	N 14	O 16	Ar 40
Be 7	53.3 d	2.9	2.5	-
C 11	20.4 min	16	8.2	-
N 13	9.96 min	17	3.4	-
O 15	2.03 min	-	34	-
Ar 41	1.83 h	-	-	660

The production of gaseous radionuclides can be estimated using an average spectrum (integrated over the emission angle) of secondary particles-predominantly neutrons - emitted from the beam interaction zone:

$$\dot{N}^{+} = n \cdot Q\ (> 15\ \mathrm{MeV}) \cdot \sigma_{eff}\ (> 15\ \mathrm{MeV}) \cdot r_{eff} \qquad (2)$$

$\dot{N}^{+}$	production rate.
Q (> 15 MeV)	source strength of neutrons with energies above 15 MeV.
σ_{eff} (> 15 MeV)	effective cross section of the activation reaction for neutrons above 15 MeV.
r_{eff}	effective radius of the activated air volume depending on the shape of the volume and on the neutron angular distribution.

The effective cross sections were derived by folding the energy dependent cross sections of the nuclear reactions with the average spectrum of neutrons with energies above the lowest threshold (> 15 MeV). The influence of neutrons below 100 MeV is significant because of their very large contribution to the total source strength and of the strong variation of the cross sections in this region. The yield of Ar 41 was estimated from the flux density of thermal neutrons in the accelerator void. From the yield of radionuclides the annual activity release from the different parts of the accelerator was estimated and used as the source term for the atmospheric dispersion. The main radiological impact is due to gamma submersion in the plume. The dominant contributions to the annual dose equivalent are caused by the positron annihilation radiation of the short lived radionuclides C 11, N 13, O 15. For a heavy ion beam of $J = 1 \cdot 10^{9} s^{-1}$, 2 GeV/u Ne-ions absorbed in a thick iron target, the total annual activity release from a 1000 m^3 target room (ventilation rate: 10 h^{-1}, beam time: 6000 h/a) is of the order of magnitude of 10^{12} Bq. At the location of maximum radiological impact the annual dose due to gamma submersion is about 1 µSv (stack height: 30 m) which is far below the dose limit for the public. Areas however where high intensity ion beams are absorbed should be supplied with an air circulation system in order to minimize the activity release and to keep the collective dose equivalent of the public as low as reasonably achievable.

SKYSHINE

In designing the shielding of the accelerator area it is important to consider neutrons which pass into the atmosphere and are scattered back to the earth thus contributing to the radiological impact. The skyshine dose rate can be described using the importance function of neutrons with given energy and emission angle for a certain distance from the source. Physically the importance function is the dose equivalent per source neutron passing into the atmosphere. The data of ref. [2] were used for the evaluation of effective importance functions by averaging over the neutron emission angle and by folding the data for monoenergetic neutrons with the average spectrum of neutrons emitted from the interaction zone of a 2 GeV/u Ne-beam (Table 3). It is essential to take into account low energy neutrons (< 10 MeV) because they largely contribute to the skyshine. The importance functions in ref. [2] contain the contribution of photons produced in neutron interactions with air. The skyshine dose rate at distance r from a beam interaction zone without roof shielding is expressed as:

$$\dot{H} = Q(\Delta\Omega) \cdot I_{eff}(r)/r^2 \tag{3}$$

$Q(\Delta\Omega)$ total source strength of neutrons emitted into the solid angle $\Delta\Omega$.

$I_{eff}(r)$ effective skyshine function at distance r from the source.

TABLE 3 Effective skyshine importance function (2 GeV/u Ne-beam)

r (m)	50	100	300	500	1000
$I_{eff}(r)$ $\left(\frac{cSv \cdot m^2}{neutron}\right)$	$2.3 \cdot 10^{-13}$	$2.3 \cdot 10^{-13}$	$2.0 \cdot 10^{-13}$	$1.4 \cdot 10^{-13}$	$5.0 \cdot 10^{-14}$

Using the data in Table 3 the skyshine dose rate caused by a target area without roof shielding was calculated from equ. (3) assumming that a beam of 10^9 s^{-1} 2 GeV/u Ne-ions is absorbed in a thick iron target (Table 4). The effective source strength $Q(\Delta\Omega)$ of neutrons above 0.1 MeV emitted from the beam interaction zone into the atmosphere is about $6 \cdot 10^{10}$ s^{-1}. The influence of a roof shielding on the skyshine dose rate was evaluated in ref. [2]. Using these attenuation factors the results given in Table 4 are obtained. The results show that at high energy accelerators with large experimental areas at ground surface level the skyshine problem needs very careful consideration with respect to the annual dose equivalent of the workers and of the population living in the vicinity of the accelerator site.

TABLE 4 Skyshine dose rate (μSv/h) caused by an experimental area without and with an ordinary concrete roof shielding

	r (m)	50	100	300	500	1000
ordinary concrete roof shielding (g/cm^2)	---	200	50	4.8	1.2	0.11
	100	48	12	1.2	0.29	0.026
	200	10	2.5	0.24	0.060	$5.5 \cdot 10^{-3}$
	300	2.0	0.50	0.048	0.012	$1.1 \cdot 10^{-3}$

REFERENCES

[1] H.-P. Weise, "Shielding of High Energy Heavy Ion Accelerators", Proceedings of the 20th Midyear Topical Symposium of the Health Physics Society on "Health Physics of Radiation Generating Machines", Reno, Nevada, Feb. 8-12, 1987, p 459.

[2] R.G. Alsmiller, JR., J. Barish, and R.L. Childs, "Skyshine at Neutron Energies $\leq$ 400 MeV", Particle Accelerators 11, (1981), pp. 131-141.